

**Detection of the 62 μ m crystalline H₂O ice feature in emission
toward HH 7 with ISO-LWS⁰**

Sergio Molinari

Infrared Processing and Analysis Center, California Institute of Technology, MS 100-22,
Pasadena, CA 91125, USA

Cecilia Ceccarelli

Laboratoire d'Astrophysique, Observatoire de Grenoble - BP 53, F-38041 Grenoble cedex
09, France

Glenn J. White

Department of Physics, Queen Mary and Westfield College, University of London, Mile
End Road, London E1 4NS, UK
Stockholm Observatory, S-133 36 - Saltsjöbaden, Sweden

Paolo Saraceno

CNR-Istituto di Fisica dello Spazio Interplanetario, Area di Ricerca Tor Vergata, via Fosso
del Cavaliere I-00133 Roma, Italy

Brunella Nisini and Teresa Giannini

Osservatorio Astronomico di Roma, via Frascati 33, I-00044 Monte Porzio, Italy

and

Emmanuel Caux

CESR CNRS-UPS, BP 4346, F-31028 Toulouse Cedex 04, France

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ABSTRACT

We report the detection of the 62 μm feature of *crystalline* water ice in emission towards the bow-shaped Herbig-Haro object HH 7. Significant amounts of far infrared continuum emission are also detected between 10 and 200 μm , suggesting that Herbig-Haro objects cease to be pure emission-line objects at FIR wavelengths. The formation of crystalline water ice mantles requires grain temperatures $T_{gr} \gtrsim 100$ K at the time of mantle formation, suggesting that we are seeing material processed by the HH 7 shock front. The deduced ice mass is $\sim 2 \times 10^{-5} M_{\odot}$ corresponding to a water column density $N(\text{H}_2\text{O}) \sim 10^{18} \text{ cm}^{-2}$; an estimate of the $[\text{H}_2\text{O}]/[\text{H}]$ abundance yields values close to the interstellar gas-phase oxygen abundance.

The relatively high dust temperature and the copious amounts of gas-phase water needed to produce the observed quantity of crystalline water ice, suggest a scenario where both dissociative and non-dissociative shocks co-exist. The timescale for ice mantle formation is of the order of ~ 400 years, so that the importance of gas-phase water cooling as a shock diagnostic is greatly diminished.

interstellar medium

Subject headings: (ISM:) dust, extinction — ISM: Herbig-Haro objects — ISM: individual (HH 7) — ISM: lines and bands — infrared: ISM: continuum — infrared: ISM: lines and bands

1. Introduction

Herbig-Haro objects (HH; Haro 1950, Herbig 1951) are emission-line objects acting as signposts for the shock regions originating at the interface between stellar winds accelerated by Young Stellar Objects (YSOs) and the circumstellar or cloud ambient material. Considerable effort was spent in the past to characterise the chemistry of these shocked regions (e.g. Draine, Roberge & Dalgarno 1983; Hollenbach & McKee 1989); dust grains are critical ingredients in these regions since many important reactions, e.g. the H_2 reformation in post-shock regions, take place on their surface. During the last twenty years infrared spectroscopy allowed the discovery of a plethora of solid-state constituents of the envelopes around YSOs: refractory material, polar and apolar ices, PAHs, etc. Yet the dust properties in the shock regions pinpointed by HH objects are poorly known; grains are poorly thermally coupled to the gas in shocks and they are warmed to only a few hundred degrees at most in dissociative shocks (Hollenbach & McKee 1989), so that their thermal emission cannot be detected below $10\ \mu\text{m}$. The origin of the UV continuum detected towards a few of these objects (Böhm, Noriega-Crespo & Solf 1993 for a review), although still not clear, is however not related to dust.

The instruments on board the *Infrared Space Observatory* satellite (ISO, Kessler et al. 1996) opened unprecedented possibilities for far infrared continuum studies of cold objects, including HH objects. In this *Letter* we present the results of the far-infrared continuum observations towards HH 7, the leading bow-shaped shock of the HH 7-11 chain emanating from the YSO SVS 13, in the star forming region NGC 1333 in Perseus ($d=350\ \text{pc}$). HH 7 has been observed with the Long (LWS, Clegg et al. 1996) and Short (SWS, de Graauw et al. 1996) wavelength spectrometers on board of ISO during revolutions 652 and 654. Details about the observations and data reduction are given elsewhere (Molinari et al. 1999). In Sect. 2 the additional data analysis

procedures we adopted to derive a reliable continuum spectrum for HH 7 are discussed. Nomenclature for the ten LWS detectors has been described in the ISO Data User Manual (http://www.iso.vilspa.esa.es/manuals/lws_idum5); detectors SW1 to SW5 cover the spectral range 43-90 μm , while detectors LW1 to LW5 cover the range 80-197 μm . The SW and LW detectors are sometimes referred to as “short” and “long” wavelength detectors respectively.

2. Results

2.1. The 62 μm feature

In Fig. 1 the 43-82 μm continuum spectra observed towards HH 7 and SVS 13 are shown. A broad feature extending from roughly 50 to 70 μm is clearly visible in the HH 7 spectrum. For clarity the SW3 detector spectrum is also shown as a dotted line which has had an offset applied to align it with the continuum of the adjacent detectors.

The primary concern was to make sure that the 50-70 μm feature was not a result of a residual instrumental effect and that it is intrinsic to HH 7. The passband calibration is already known to be somewhat inaccurate for detector SW1. This *Ge:Be* detector suffers the most severe memory effects amongst the LWS detectors and its calibration accuracy may worse than 50%. The response of this detector is also a sensitive function of the incident radiation flux, as well as of the past illumination history, and of the impact rate of high-energy particles onto the detector. Such effects are known to be far less severe for the SW2, SW3 and SW4 detectors, for which a conservative figure of 30% can be assumed for the calibration accuracy.

Another instrumental effect which could be responsible for the appearance of spurious spectral features is a result of near-IR leaks through the passband

filters in front of the ten LWS detectors. The available related documentation (http://isowww.estec.esa.nl/notes/lws_0197.html) shows that there are known spurious features which can occur around 52 and 57 μm , with FWHM of the order of $2\mu\text{m}$; such features could not possibly lead to the broad feature visible on Fig. 1.

Finally, this feature might result from contamination effects from the bright nearby source SVS 13, which is the candidate exciting source for HH 7. Such contamination effects, which should however affect the overall continuum spectrum and that are expected to be more severe for long wavelength detectors, will be discussed in detail in the Sect. 2.2. We just note here that if the 50-70 μm feature seen on the HH 7 spectrum was due to a fraction of the flux emitted by the nearby contaminating source SVS 13, we would expect to see the same feature at a comparable “line-to-continuum” ratio on the SVS 13 continuum spectrum; Fig. 1 clearly shows that this is not the case. We conclude that the 50-70 μm feature is real and intrinsic to HH 7. We identify this as the 62 μm feature due to the longitudinal acoustic modes of crystalline water ice (Bertie, Labbe & Whalley 1969). This feature was observed for the first time by Omont et al. (1990) in the expanding envelopes of post-AGB stars, while recent ISO observations have identified this feature in the spectra of a few Herbig Ae/Be stars (Waters & Waelkens 1998, Malfait et al. 1999). It is the first time such feature has been detected towards Herbig-Haro objects.

2.2. The 2-200 μm Continuum

SWS line scans were used to estimate the continuum at several wavelengths for $\lambda < 40 \mu\text{m}$. For each line scan, the portion of the spectrum where line emission was present (Molinari et al. 1999) was eliminated, and the remaining points were used to build the density functions of the observed flux. A gaussian was then fitted to the core of the distribution to obtain the centroid (average flux) and the standard deviation which, divided

by the square root of the number of points, allowed a formal estimate of the associated uncertainty. These uncertainties reflect the internal accuracy of the estimates; infact the true uncertainty may be higher. In particular, all data shortward of $\sim 10 \mu\text{m}$ are at the detection limit of the SWS and we will treat them as 1σ upper limits.

LWS scans were averaged using the ISO Spectral Analysis Package (ISAP, <http://www.ipac.caltech.edu/iso/isap/isap.html>) using a median clipping algorithm which rejected outlying data points which are mainly due to incomplete removal of glitches from cosmic rays. The averaged LWS spectra observed towards HH 7 are presented in Fig. 2a, where it can be seen that significant levels of continuum are clearly detected over the whole spectral range. However, contamination effects in the HH 7 spectrum due to the nearby ($\sim 70''$ NW) candidate exciting source SVS 13 must be taken into account to assess if the detected continuum is all due to HH 7. Although the examination of LWS spatial scans across point-like sources suggests that the contamination fraction is of the order of a few percent by a distance of $\sim 70''$ off-axis, this small contamination fraction may become significant when the contaminating source is intrinsically much brighter than the on-axis source. This is the case for SVS 13, whose spectrum rises to more than 400 Jy at $\lambda \gtrsim 100 \mu\text{m}$.

To accurately estimate the amount of contamination which the HH 7 continuum suffers from SVS 13 we analysed the data collected from the LWS as part of the LWS calibration programme during a few revolutions in August 1998, when an irregularly sampled raster map of Mars was taken to evaluate the response of the instrument focal plane. The full data set is still under analysis by the LWS consortium, but we consider here the small subset of data covering the beam portion where SVS 13 was located during the HH 7 observations. We used the LIA (<http://www.ipac.caltech.edu/iso/lia/lia.html>) routine INSPECT_RASTER to determine the relative position of HH 7 and SVS 13 in the

[Y,Z] spacecraft frame of reference. We then considered the Mars spectra taken on-axis, along the direction connecting the two sources, and we averaged the data detector by detector. Each detector average at the various off-axis positions was then ratioed to the analogue detector average of the on-axis spectra; this allowed us to estimate a set of ten contamination factors for each off-axis position along the line joining HH 7 and SVS 13. We then used a spline interpolation to estimate these factors (one per detector) at an off-axis distance of $68''$ (the distance between HH 7 and SVS 13); we obtain the following values for the ten detectors respectively: 0.024, 0.025, 0.037, 0.05, 0.075, 0.09, 0.10, 0.11, 0.13, 0.15. These factors increase with wavelength as expected due to the increasing importance of diffraction. The observed SVS 13 spectra were then multiplied by these factors, and the resultant spectrum was subtracted from the observed HH 7 spectrum. The HH 7 spectrum obtained with this procedure is shown in Fig. 2b.

This method for estimating the contamination from nearby sources inevitably suffers from the irregular sampling of the Mars raster map. Raster points did not lay exactly along the HH 7-SVS 13 direction on the focal plane, and the interpolation between the correction factors estimated at each relevant raster position also introduced an additional uncertainty. In spite of this, comparison between Fig. 2a and b shows that the overall HH 7 spectrum appears more internally consistent once the estimated contamination effects are taken into account. In particular, the jump visible in the 'observed' spectrum between the SW and the LW detectors (at $\lambda \sim 90 \mu\text{m}$) disappears after the correction is made; on the other hand, we find worse alignment between adjacent LW detectors. We believe this may be due to the fact that we adopted a single correction factor for each detector, while instead the contamination factor varies across the bandwidth of each detector; the variation is more severe for LW detectors since they also experience heavy fringing. A proper treatment would require an estimate of the corrections as a function of both the detector and wavelength, but we decided not to include an additional source of uncertainty

in the process. Fig. 2b shows that the short wavelength part of the spectrum depends more critically on the particular value of the contamination factor; doubling this factor would lower the $\lambda \leq 80 \mu\text{m}$ part of the spectrum to negative flux levels. If the $\lambda \leq 80 \mu\text{m}$ flux observed towards HH 7 were due to contamination, however, we would expect to see the $62 \mu\text{m}$ emission feature also on the continuum spectrum of SVS 13 and with a comparable “line/continuum”; instead, no trace of such a feature is seen on the SVS 13 continuum (see Sect. 2.1). Finally, the amount of continuum flux for $\lambda \geq 90 \mu\text{m}$ is high enough not to be significantly influenced by the particular estimate of the contamination factors.

We conclude that FIR emission which is intrinsic to HH 7 has been detected, showing for the first time that Herbig-Haro objects cease to be exclusively emission-line objects at FIR wavelengths.

3. Discussion

In the following discussion we will consider the $62 \mu\text{m}$ feature together with continuum spectral points derived from our SWS observations, and with the 1.25 mm continuum data obtained by Lefloch et al. (1998). The spectral energy distribution from HH 7 will be modeled as thermal emission from dust grains composed of a silicate core and a water ice mantle. The absorptivity as a function of wavelength is computed from the complex refractive index using Mie theory in the formulation of Wickramasinghe (1967). Complex refractive indices for crystalline water ice in the range $2\text{--}300 \mu\text{m}$ were taken from Bertie et al. (1969), while silicate indices were computed from the complex dielectric function tabulated by Draine (1985). Longward of $300 \mu\text{m}$ the silicate absorptivities by Draine (1985) were adopted; inclusion of water ice mantles may steepen the slope of the Q_{abs} vs λ relationship (Aannestad 1975) in the submillimeter and millimeter wavelength ranges, possibly leading to underestimation of the dust mass. Radiative transfer is approximated

with an analytical treatment where dust is distributed on a sphere which is characterised by radial density and temperature gradients (Noriega-Crespo, Garavich & Molinari 1998). The results of millimeter wavelength continuum mapping (Lefloch et al. 1998) indicate the presence of a cold dust clump centered on the location of HH 7; this clump extends over a larger area than the one traced by the optical or near-IR emission; a treatment where a dust clump is centrally heated by the HH 7 shock seems therefore appropriate.

Fig. 3 presents the complete spectral energy distribution observed towards HH 7. The LWS detectors SW1 to SW4, originally shown in Fig. 1, have been rescaled to a common level preserving their original mean value; no other rescaling was made to the rest of the LWS spectra. The continuum points from the SWS spectra and an estimate for the 1.25 mm flux integrated on the model fit area are also reported; the 1.25 mm flux estimate should be considered as an upper limit, since the flux has been integrated with uniform weighting. We find that it is impossible to globally fit the observed spectral energy distribution; consequently priority was given to the short wavelength LWS detectors spectra because these are the ones showing the $62\ \mu\text{m}$ feature, and more closely match each other in both absolute and relative terms. The LWS LW detectors on the contrary are those for which the contamination fraction from nearby sources is higher and for which diffraction and source’s extension effects (which here have been neglected) are more severe. An additional complication for the LW detectors, which the SW detectors do not suffer from, is that heavy fringing is observed (which has been removed for cosmetic purposes in the presented plots). This has the effect of modulating the beam size as a function of wavelength even within individual detector bands; we did not take this into account, instead deriving a single contamination factor per detector. However, dividing a spectrum by a constant has the effect of changing the slope; this seems the case comparing the LW detectors in Figs. 2a and b. Data from the long wavelength LWS detectors are therefore considered important to assess the presence of intrinsic FIR continuum toward HH 7, but they are not taken into

account in the detailed model fit.

While the overall appearance of the continuum depends on the radius of the dust clump, its mass and temperature gradient, the “line/continuum” ratio of the $62\ \mu\text{m}$ feature depends on the relative size of the ice mantle with respect to the grain core. The $62\ \mu\text{m}$ water ice feature is well fitted by adopting a core radius of $0.07\ \mu\text{m}$ and a total core + mantle radius of $0.1\ \mu\text{m}$. It is interesting to note that the model also suggests that the short wavelength end of the LWS spectrum can be identified with one side of the $45\ \mu\text{m}$ water ice feature, also in emission; such feature, in absorption, has already been detected with ISO towards YSOs (Dartois et al. 1998). The only continuum points on the other side of the $45\ \mu\text{m}$ feature, at $\lambda \sim 38.4\ \mu\text{m}$, are also in excellent agreement with the model, although we reiterate (see also Sect. 2.1) that the SW1 detector is the one that experiences the most severe problems in calibration-related aspects. The importance of the detection of the $62\ \mu\text{m}$ feature is that it is specific to crystalline water ice, as opposed to the $45\ \mu\text{m}$ feature which is instead predicted for both crystalline and amorphous ice (Moore et al. 1994). In this respect, laboratory studies (e.g. Smith et al. 1994) show that the $62\ \mu\text{m}$ feature is an important indicator of the temperature of the grains because it appears at $T \gtrsim 100\ \text{K}$ when an irreversible transition from amorphous to crystalline state commences. The $45\ \mu\text{m}/62\ \mu\text{m}$ feature ratio could also be used to diagnose the thermal history of the ice mantles (Smith et al. 1994); direct deposition of ice mantles onto grains at $T \gtrsim 100\ \text{K}$ should produce a higher $45\ \mu\text{m}/62\ \mu\text{m}$ ratio as opposed to warm-up of ice mantles deposited at lower temperatures.

The fit plotted in Fig. 3 is obtained adopting a dust clump radius of $0.06\ \text{pc}$, which approximates the radius of the average LWS beam size at a distance of $350\ \text{pc}$, and the size of the $1.25\ \text{mm}$ continuum emission area (Lefloch et al. 1998). The density is assumed constant and equal to $6 \times 10^{-4}\ \text{cm}^{-3}$ while the temperature varies from ~ 10 to $200\ \text{K}$ (but

we verified that the model is not very sensitive to the upper temperature envelope) with a ~ -0.4 power-law radial gradient. The bolometric luminosity obtained integrating the model fit is $L_{fit} = 3.7 L_{\odot}$, while integration of the contamination-corrected SED (Sect. 2.2) yields $L_{sed} \lesssim 4.5 L_{\odot}$ (since $\lambda < 10 \mu\text{m}$ and $\lambda = 1.25 \text{ mm}$ data are to be considered upper limits); this is about a factor 30 higher than the cooling via atomic and molecular lines observed towards HH 7 (Molinari et al. 1999). The fitted model predicts that the bulk of the $62 \mu\text{m}$ feature is emitted by dust at temperatures $T \gtrsim 30 \text{ K}$ concentrated inside a $4''$ -radius region centered on HH 7, a size comparable to that of the optical and near-IR emission which traces the shock front. The existence of crystalline water ice mantles necessarily implies that the dust must have experienced a rise in temperature to values $\gtrsim 100 \text{ K}$; since the grains can attain these temperatures in shock cooling regions (Hollenbach McKee 1989), **the $62 \mu\text{m}$ feature most likely originates from dust which has been processed by the HH 7 shock.** The dust mass in the $4''$ -radius region centered on HH 7 where the bulk of the $62 \mu\text{m}$ feature originates, amounts to $5 \times 10^{-5} M_{\odot}$ (the total dust mass implied by the model fit is $\sim 0.035 M_{\odot}$); the relative proportion of core and mantle (the core has 70% of the total grain radius) implies a water ice mass of $2 \times 10^{-5} M_{\odot}$, or a H_2O column density $\sim 1.1 \times 10^{18} \text{ cm}^{-2}$. H_2 pure rotational lines (Molinari et al. 1999) detected with ISO towards HH 7 suggest temperatures of about 550 K and a H_2 column density $\sim 4.4 \times 10^{20} \text{ cm}^{-2}$ in the same $4''$ -radius region where the bulk of the water ice feature supposedly comes; the estimated abundance, $[\text{H}_2\text{O}]/[\text{H}] \sim 1.25 \times 10^{-3}$, seems unreasonable since it is a factor ~ 4 higher than the interstellar O gas-phase abundance (Meyer et al. 1998). However, this number should be regarded as an upper limit because we cannot exclude the presence of cold H_2 ($T \lesssim 100 \text{ K}$) which our ISO observations (Molinari et al. 1999) would not trace; besides, a hotter ($T \gtrsim 2000 \text{ K}$) H_2 component was detected by Gredel 1996) but with a 3 orders of magnitude lower column density. This water abundance, even if considered only as an order-of-magnitude estimate, is however much higher than the gas phase water

abundance ($[\text{H}_2\text{O}]/[\text{H}] \lesssim 10^{-5}$) deduced from FIR lines (Molinari et al. 1999), and it would essentially imply that most of the oxygen is locked into water ice.

Due to the uncertainty about the $45\ \mu\text{m}$ feature (see above), it is hard to tell from the observational viewpoint whether gas-phase water produced behind the HH 7 shock front (Kaufman & Neufeld 1996) is deposited onto warm grains, or pre-existing ice mantles are warmed-up during the passage of a relatively gentle shock front. The ice optical constants that we used (Bertie et al. 1969) are from laboratory samples obtained by direct deposition at $T=173\ \text{K}$ and subsequent cooling to $100\ \text{K}$; hence the good simultaneous fit of the 62 and $45\ \mu\text{m}$ features would tend to support the first scenario. It is well known that the physical condition behind low velocity ($v_s \lesssim 40\ \text{km s}^{-1}$), non-dissociative, shocks are favourable for the rapid gas-phase incorporation of atomic oxygen into water (Draine, Roberge & Dalgarno 1983, Kaufman & Neufeld 1996). Subsequent freezing onto grains (Bergin, Neufeld & Melnick 1998, 1999) in the cooling post-shock region could produce the observed water ice mantles, also explaining the minor role played by gas-phase water in the cooling of the HH 7 shock (Molinari et al. 1999). Non-dissociative shocks are however unable to raise the grain temperature to the $T \gtrsim 100\ \text{K}$ (Draine, Roberge & Dalgarno 1983) needed to explain the presence of *crystalline* ice mantles since shocked gas mainly cools in the infrared where dust absorptivity is not high; the situation is different behind dissociative shocks, where the intense UV field generated (Hollenbach & McKee 1989) is much more efficient in heating the grains. The co-existence of both types of shock, which is needed to explain the present observations, is also an expected feature of bow shocks like HH 7 (Smith & Brand 1990) and it is independently supported by FIR lines studies (Molinari et al. 1999).

The alternative possibility that pre-existing amorphous water ice mantles are heated up during the passage of the shock front seems unlikely since the mantles are easily destroyed by grain-grain collisions once the shock velocities exceed $\sim 15\ \text{km s}^{-1}$ (Caselli, Hartquist &

Havnes 1997).

We can derive an order-of-magnitude estimate for the timescale τ_{ice} of the formation of water ice mantles, by dividing the linear size of the post-shock region by the shock velocity; assuming a maximum shock velocity of $\sim 40 \text{ km s}^{-1}$ for the HH 7 shock (Solf & Böhm 1987, Molinari et al. 1999) and a linear extent of $\sim 10''$ for the HH 7 post-shock region as estimated from H_2 $2.12\mu\text{m}$ images (Garden et al. 1990, Everett 1997, Molinari et al 1999), we estimate $\tau_{ice} \sim 400 \text{ yrs}$, a factor ~ 250 less compared to theoretical predictions for ice mantles formation behind non-dissociative shocks (Bergin, Neufeld & Melnick 1999). In this case the gas-phase water cooling is practically irrelevant as a shock diagnostic.

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Fig. 1.— LWS averaged spectra observed towards HH 7 (bottom) and SVS 13 (top). The four portions are the 4 LWS detectors SW1 to SW4, covering the following spectral ranges respectively: [43.2, 50.0], [49.7, 63.7], [58.1, 69.5] and [67.3, 81.7]. An emission feature extending from $\sim 50 \mu\text{m}$ to $\sim 70 \mu\text{m}$ is clearly visible in the HH 7 spectrum, which is not visible in the SVS 13 spectrum. The [OI]63 μm fine-structure line is also recognised. The dotted spectral portion for HH 7 represents detector SW3 with an applied offset of 5 Jy to bring it in line with the other detectors.

Fig. 2.— On the left side we show the 43-197 μm LWS averaged spectrum observed towards HH 7; the binsize for averaging is 0.5 μm . The right panel shows the same spectrum after the correction for contamination from SVS 13 was taken into account as described in text.

Fig. 3.— Complete spectral energy distribution towards HH 7. The full lines represent the LWS spectra after applying the contamination corrections discussed in the text. Detectors SW1 to SW4 have been rescaled to a common level preserving their original mean value, while no scaling is applied to the other LWS detectors. Asterisks represent the continuum points derived from our SWS observations, while the diamond represents the 1.25mm flux integrated with uniform weight in the model fit area; this should be regarded as an upper limit. The dashed line is the model fit as described in the text.

Possible Papers that are based on the PHT-S data

Highlights:

- The mid-Infrared Spectra of Normal Galaxies (Helou et. al., submitted to ApJ Letter)

Data and Analysis Papers:

- Infrared Emission of Normal Galaxies from 3 to 12 Microns (Lu et. al., in preparation)
 - data presentation and statistical analyses
- Synthesize the galactic emission in mid-IR
 - compare with spectra of Galactic sources (HII, PDRs, diffuse medium, etc.)]
-

Papers on PAH Theory:

- C⁺⁺/PAH correlation and Gas Heating and Cooling in the ISM
- Testing PAH models





